

Faraday and the Structure of Matter

by L. PEARCE WILLIAMS

Department of History,
Cornell University, Ithaca, New York.

SUMMARY

Michael Faraday, the experimentalist, is a well-known and beloved figure in the history of science; Michael Faraday, the theorist, is almost a stranger. The purpose of this paper is to describe Faraday's theoretical ideas on the structure of matter and to illustrate his use of these ideas as guides in his researches on electrolysis, static induction and ordinary electrical conduction.

1. INTRODUCTION

Michael Faraday is rightly regarded as the greatest experimentalist in the history of science. The three volumes of the *Experimental Researches in Electricity* are not only one of the master works of science but a unique record of sustained experimental investigation. And the achievement is awesome; with what patience did Faraday coax and cajole Nature to reveal her secrets; with what skill did he torture each new fact to ensure that it was a fact and not merely an illusion!

But Faraday's very skill as an experimenter, together with his apparent distrust of theory, served to create a myth which still persists. It is the myth that Faraday was the perfect Baconian. His success was attributed to his seeming willingness to remain an objective collector of facts. Since Faraday's career coincided with the revival of Baconianism considered as a (indeed *the*) proper scientific method, the origins of the myth are easily explained. Like most myths, it has endured far beyond the time when it might be supposed to reflect reality. For the creators of the myth, Faraday's greatness *did* lie in his discovery of new facts such as the rotation of a current-carrying wire around a magnetic pole, electromagnetic induction, diamagnetism, and the rotation of the plane of polarized light in a magnetic field. Since the publication of Einstein's General Theory of Relativity, however, we must see Faraday in a different perspective. Can the foundations of field theory be only the accidental by-products of clever laboratory manipulation, or must we not recognize that the hand of the skilful experimenter was directed by the keenest theoretical mind of the nineteenth century? Actually, each discovery had been suggested by theoretical considerations, and each newly discovered fact became, in turn, part of the structure of theory. It is not my purpose here to examine this theoretical structure in its entirety for that would necessitate going far beyond the limits of a short article. What I should like to do is present Faraday's ideas on the constitution and structure of matter and show, in some detail, how these served as the guide for his first important series of experimental investigations.

2. FARADAY AND THE ATOMIC THEORY

Faraday's attitude toward the atomic theory has generally been used to illustrate his caution and distrust of 'hypotheses'. In 1844, when the atomic theory was the acknowledged basis of chemistry, with the full weight of the authority of Berzelius (and most chemists) behind it, Faraday wrote:

" The view of the atomic constitution of matter which I think is most prevalent, is that which considers the atom as a something material having a certain volume, upon which those powers were impressed at the creation, which have given it, from that time to the present, the capability of constituting, when many atoms are congregated together into groups, the different substances whose effects and properties we observe. These, though grouped and held together by their powers, do not touch each other, but have intervening space, otherwise pressure or cold could not make a body contract into a smaller bulk, nor heat or tension make it larger; in liquids these atoms or particles are free to move about one another, and in vapours or gases they are also present, but removed very much further apart, though still related to each other by their powers.

" The atomic doctrine is greatly used one way or another in this, our day, for the interpretation of phenomena, especially those of crystallography and chemistry, and is not so carefully distinguished from the facts, but that it often appears to him who stands in the position of student, as a statement of the facts themselves, though it is at best but an assumption; of the truth of which we can assert nothing, whatever we may say or think of its probability. The word atom, which can never be used without involving much that is purely hypothetical, is often *intended* to be used to express a simple fact; but good as the intention is, I have not yet found a mind that did habitually separate it from its accompanying temptations; and there can be no doubt that the words definite proportions, equivalents, primes, etc., which did and do express fully all the *facts* of what is usually called the atomic theory in chemistry, were dismissed because they were not expressive enough, and did not say all that was in the mind of him who used the word atom in their stead; they did not express the hypothesis as well as the fact."

Faraday's objection to the atomic theory was not only that it went beyond experience but also that it failed to account for a whole host of phenomena. By 1844, indeed, it was almost impossible to speak of *an* atomic theory. There were different kinds of atoms, each suited to account for certain observed facts, but none sufficient to explain them all. To account for chemical combination in definite proportions, Dalton had introduced his 'billiard ball' atoms which by their indivisibility, gave an ultimate physical reality to these combining ratios. From his work on gases, he also recognized the necessity of having a repulsive principle to account for the rarefaction and expansibility of aeriform substances; thus, each 'billiard ball', endowed with the attractive principle of universal gravitation, was surrounded by an atmosphere of caloric (the 'fluid' of heat) which repelled other similarly equipped atoms. The discovery of the electrolytic properties of the voltaic pile led Berzelius to suggest an atom whose opposite ends contained equal charges of positive and negative electricity. The atom, as a whole, was electrically neutral, yet would respond to the electrical forces of the pile and enable one to account for the observable electrochemical decompositions. After Oersted's demonstration of the magnetic effects of an electric current in 1820, Ampère proposed another kind of atom in which a positively charged nucleus was surrounded by a current of negative electricity. Magnetic effects were thereby reduced to the results of the alignment of these electro-dynamic atoms. Faraday's own discovery of diamagnetism gave rise to still another atom in which the electric currents were so arranged that the particles would set themselves across, rather than along, the lines of magnetic force.

This proliferation of atomic models when thus baldly stated would appear to militate against the acceptance of the atomic theory by any thinking person in the nineteenth century. But with the exception of a few men like Faraday, such a confrontation of mutually incompatible schemes rarely took place. In fact, they proved most useful in the limited areas to which each concept was

applied by the active research scientist. Not the least valuable of the many lessons of the history of science is that of the importance of ignoring 'details' which get in one's way. For the analytical chemist, 'billiard balls' were sufficient and if it was objected that they could not explain the origin of electric or magnetic forces, the tendency was for him to shrug his shoulders and suggest vaguely that an imponderable electric or magnetic fluid could take care of that difficulty. Similarly, the physicist interested in electrical effects could more or less ignore the problems of chemical combination in *his* atomic theory. The fruits of this method should be noted. By disregarding side issues, the analytical chemists produced the periodic table; from the physicist came the discovery of the electron and the 'sub-atomic' particles.

To Faraday, however, the situation was more complicated. Like Berzelius, he was an analytical chemist of considerable skill; like Gay-Lussac and Dalton, he was applauded by the scientific community for his work on gases; like Oersted and Ampère, he created a new epoch in the study of electromagnetism; like Fresnel and Young, he contributed fundamentally to the theory of light; like Sir Humphry Davy, he was a founder of electrochemistry. Unlike these men, he worked almost simultaneously in all these fields. The annoying but seemingly irrelevant 'detail' of one area loomed as an impassable barrier in another. As early as 1817, Faraday had recognized the dangerous (and human) desire to theorize over-hastily thereby gaining present certainty at the expense of future error. "Better" he wrote "to own our ignorance of these phenomena, if we cannot by their means ascertain satisfactorily the true circumstances of the case, than to form an hypothesis which shall in accounting for a single instance give birth to a thousand chimera elsewhere."

Faraday, keenly aware of the inadequacies of the commonly held atomic theories, did not suggest (as some did) that all such theoretical considerations be expelled from science. Quite the contrary; part of his hostility to the ordinary concept of atoms arose from the fact that he was the ardent promoter of another atomic theory which, he felt, did account adequately for phenomena. Moreover, this theory had the further advantage, in Faraday's eyes, of being based on a minimum of speculation and hypothesis.

"If we must assume at all, as indeed in a branch of knowledge like the present we can hardly help it, then the safest course appears to be to assume as little as possible, and in that respect the atoms of Boscovich appear to me to have a great advantage over the more usual notion. His atoms, if I understand aright, are mere centres of forces or powers, not particles of matter in which the powers themselves reside. If, in the ordinary view of atoms, we call the particle of matter away from the powers a , and the system of powers or forces in and around it m , then in Boscovich's theory a disappears, or is a mere mathematical point, whilst in the usual notion it is a little unchangeable, impenetrable piece of matter, and m is an atmosphere of force grouped around it.

"In many of the hypothetical uses made of atoms, as in crystallography, chemistry, magnetism, etc., this difference in the assumption makes little or no alteration in the results, but in other cases, as of electric conduction, the nature of light, the manner in which bodies combine to produce compounds, the effects of forces, as heat or electricity, upon matter, the difference will be very great."

It is my contention that Boscovich's atomic theory provided the basic theoretical framework for Faraday's most important work, at least until the discovery of diamagnetism in 1845. If we are to understand Faraday's development, therefore, we must first examine this theory and the circumstances in which Faraday became acquainted with it.

3. BOSCOVICH'S ATOMIC THEORY

In 1763, Father Roger Joseph Boscovich, S.J., published his *Theoria Naturalis* in Venice. In this work he attempted to avoid some of the problems implicit in the conventional (Newtonian) corpuscular philosophy. The question of the mechanism of impact was of particular urgency, for Boscovich saw that it was not possible merely to reduce billiard balls to atomic size and let them bounce into one another. Ultimate particles must, by definition, be incompressible for there is no space into which the parts (which cannot exist) of an atom can be compressed. What, then, happens when two atoms collide? Without compression and elastic deformation, impact and rebound must be instantaneous. If atom A strikes B, at the moment of impact A will have two velocities, which is absurd. To avoid this absurdity, Boscovich eliminated

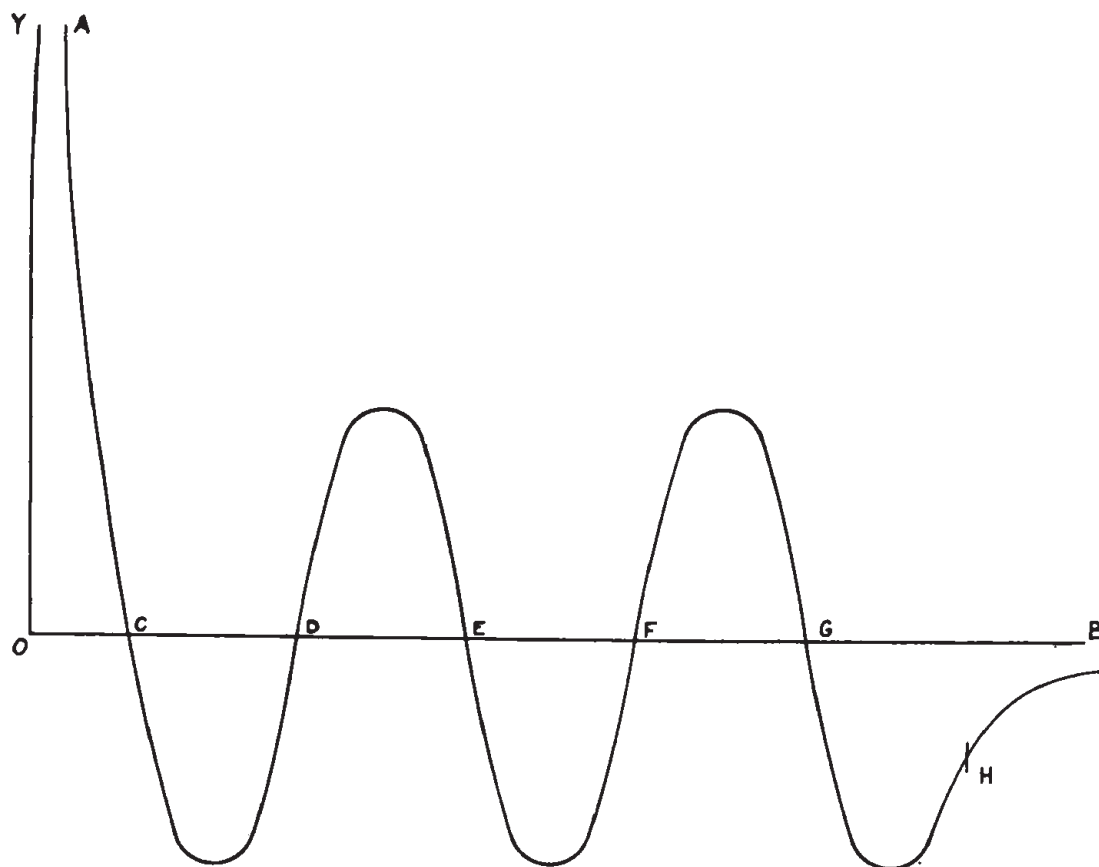


Fig. 1. Boscovich's curve of atomic forces.

the material aspect of the atom and reduced it to a mathematical point surrounded by alternating shells of attractive and repulsive forces. In fig. 1, OB is a measure of the distance from the mathematical point-centre of force at O; repulsive forces are represented by the loops of the curve above OB; attractive forces by the loops below OB. At C and H these alternating forces change character. AC is asymptotic to OY. As one approaches O the repulsive force approaches infinity, thus preserving the property of impenetrability. At H, receding from

the centre of force, the curve is transformed into a hyperbola, asymptotic to OB and representing the inverse square law of universal gravitation. Boscovich carefully avoided putting dimensions on this figure, except to make a basic dividing line at H. To the right of H we are in the macroscopic world; to the left is the realm of atomic interaction.

Boscovichean atoms retained all the properties of the Newtonian corpuscles. The repulsive forces gave them solidity, impenetrability and elasticity; the existence of the forces in space provided extension; the atoms gravitated towards one another and followed the Newtonian laws of motion. More important than the similarities were the differences, for it was these which gave the Boscovichean system its considerable advantage over the older scheme. This advantage was particularly striking in the area of chemistry. Consider, for a moment, the problem of the origin of the perceptible qualities of bodies. This problem had occupied chemical philosophers since antiquity when the atomic hypothesis was first proposed. Two general atomic schemes had been suggested, both ultimately locating the origin of sensible qualities in atomic (or molecular) configuration. Thus, the chemist could assume either differently shaped atoms or round atoms aggregated into definite shapes and then attempt to explain chemical phenomena by means of these geometrical forms. For example, acids were able to corrode other bodies, because they had sharp points and could penetrate the narrow pores of dense bodies such as metals. The difficulty in this system lay in accounting for the regularity of the chemical forms. Why, if universal gravitation were the only force at work, should there be the production of geometrically perfect (and for each compound, constant) forms instead of amorphous clumps? And why should there be 'elective attractions' so that a substance, inert in the presence of one reagent, reacted vigorously with another? Such questions were unanswerable in the old system and even led Lavoisier to reject the whole atomic speculation as essentially metaphysical and meaningless. With Boscovichean atoms, however, these problems were easily solved. From the primitive centres of force, more complex and geometrically regular assemblages of atoms could be built up whose stability was the result of the complex interaction of the atomic forces. These bodies, the chemical elements, reacted in turn with others to create molecular forms, again rigidly determined by the patterns of the forces involved. Reactions took place when the forces of two elementary particles could mesh in such a way that a stable compound could be formed. The stability of the compound was determined by the strength of the forces involved.

Even on the macroscopic level, the problem of form was more easily handled with Boscovichean atoms than with material particles. How and why did particles assume the regular positions they did in crystalline bodies? If material bodies were affected only by the attractive force of gravitation and the repulsive force of caloric how could one account for the constancy of crystalline form exhibited by mineral species? Once again, the Boscovichean system removed these difficulties by considering geometrical form as the result of the complex interlocking of atomic or molecular forces.

Problems of change of state, too, could be more easily understood in the Boscovichean system. The stability of physical states over a relatively wide range of temperature could be directly related to the alternating attractive and repulsive forces of the constituent particles. The specific and constant transition

points (i.e. melting and boiling points) could be located as the various neutral points on the Boscovichean curve.

When Boscovich presented his ideas, chemists were in no position to utilize them. As the eighteenth century advanced, the general current of chemical thought ran increasingly stronger against this kind of 'metaphysical' speculation, which, though seductive, appeared to be beyond the realm of experimental verification. As Lavoisier wrote in his *Elementary Treatise on Chemistry*,

"All that can be said about the number and nature of elements seems to me to be discussions which are purely metaphysical, to be indeterminate problems capable of an infinite number of solutions, not one of which, in all probability is consistent with nature. I shall, therefore, content myself with saying that if, by the term elements we mean to express the simple and indivisible molecules that compose bodies, it is probable that we know nothing about them. . . ."

The firm philosophical foundation on which Lavoisier wished to place chemical science derived from this attitude; chemistry was a science of *facts*, not theories. Elements were the last term of a laboratory analysis; 'principles' were not metaphysical entities (like pointed acid particles) but ponderable substances whose presence conferred certain properties upon compounds containing them (i.e. oxygen as the acid-forming substance presumed to exist in all acids). In this scheme there was no room for Boscovich.

When Lavoisier's system (but not his method) came tumbling down with the discovery of the elementary nature of chlorine and, hence, of the non-existence of oxygen in one of the strongest acids, the old problem of the origin of chemical properties once more became intrusive. Furthermore, with the discovery of the voltaic pile in 1799 and the realization that electricity played a major role in chemical combinations, there was a strongly-felt desire for some theoretical background against which the host of new discoveries which followed could be viewed. It is, I think, no coincidence that Sir Humphry Davy, who established chlorine as an element and whose work in electrochemistry was fundamental was a strong Boscovichean. Just when he became a proponent of Boscovichean atomism I have not been able to determine, but his first serious use of it was after he became convinced that chlorine was not a compound of some unknown base and oxygen as demanded by Lavoisier's theory. Now, if chlorine were an element, then chemistry was in the rather uncomfortable situation of being unable even to give a definition of an acid. The best one could do was say that an acid was a substance which turned litmus pink. Davy, rather tentatively at first, and then with more and more confidence, insisted that acidity was the result of molecular form rather than of the presence of some ponderable or imponderable 'acidifier'. With this in mind, he turned to the analysis of the acids of phosphorus, but without notable results. With more success, he established that the diamond was pure carbon. The enormous differences in the properties of the diamond and ordinary carbon were solely the result of the modification of the geometrical arrangement of the carbon particles.

During these years, Faraday was Davy's assistant, working at the master's elbow and eagerly snatching up everything he could in the way of chemical theory and practice. There can be little doubt that it was through Davy that Faraday was first introduced to Boscovich's theory. In Davy's *Common-Place Book* for 1815-16, in which both Faraday and Davy wrote notes and jottings, there is a passage, probably by Faraday, in which Boscovich's theory is used to explain 'all the phenomena of chemistry'. In a series of lectures on chemistry

which he delivered before the City Philosophical Society, a group of young men dedicated to self-improvement to which he belonged, Faraday again brought forward the doctrine of immaterial atoms as being worthy of consideration by his audience. For the most part, however, during the years from 1816, when he published his first paper, to 1831 when he began his classical researches on electrochemistry, Faraday was occupied with matters which strained his practical abilities to the utmost but required little in the way of theoretical reasonings. We must, of course, except his discovery of the rotation of a current-carrying wire around a magnetic pole in 1821 and his discovery of electromagnetic induction in 1831. Even here, the role of theory was rather limited. Faraday himself tells us that it was while writing a history of electromagnetism that he saw that a current-carrying wire should rotate around a magnetic pole and, with his unusual manipulative skill and insight, envisioned the apparatus necessary to illustrate the expected effect. The discovery of electromagnetic induction derived almost entirely from Faraday's deeply felt conviction of the symmetry of nature; if, as Oersted had shown, an electric current could produce magnetic effects then the converse must be true and the real problem was to devise the proper apparatus to make the effect manifest. For the rest, this period was almost entirely devoted to running rather standard qualitative or quantitative analyses and to the highly empirical investigations on the alloys of steel and on glass manufacture.

There is one discovery during this time that deserves special mention for it is the first instance, to my knowledge, where the theory of immaterial atoms led to a specific and new result. It was Davy, however, and not Faraday who foresaw the unexpected. Faraday had been working for some time with crystals of the hydrate of chlorine when, in the early spring of 1823, Davy suggested that he heat the crystals in a closed glass tube. The result was the liquefaction of chlorine which both Davy and Faraday mistakenly thought to be the first condensation of a so-called 'permanent' gas. Davy, in a note appended to the paper announcing this discovery, wrote:

"In desiring Mr. Faraday to expose the hydrate of chlorine to heat in a closed glass tube, it occurred to me that one of three things would happen: that it would become fluid as a hydrate; or that a decomposition of water would occur, and euchlorine and muriatic acid be formed; or that the chlorine would separate in a condensed state."

If we believe Davy, and in the absence of any evidence for disbelief I think we must, then we have to ask why he felt that the application of heat could lead to the liquefaction of chlorine. According to the Daltonian theory such a result would be quite impossible, for the addition of heat, the principle of repulsion, should lead rather to rarefaction than condensation. Davy's suggestion, however, makes rather good sense when looked at from the viewpoint of immaterial centres of force. The chlorine particles, bound in the crystals of the hydrate, existed in close proximity to one another and to the particles of water. To produce liquid chlorine, the water must be driven off and the chlorine particles stabilized at the atomic distance of a liquid. Davy, holding heat to be the motion of the constituent particles of a substance, no doubt felt that the slow increase of molecular agitation might loosen the bonds by which the water particles were held and force the chlorine molecules into another, more stable and mutually more intimate association. Referring to the curve in fig. 1, heat as motion might push the chlorine particles over the 'hump' of repulsion, from say G to F, thus reducing the whole to a liquid.

This use of the theory of immaterial atoms should be noted for there can be no doubt that Faraday's acceptance of it came about largely as a result of witnessing its utility and power in Davy's hands. There were three aspects of the theory which appealed irresistibly to Faraday. There was the fact that, although hypothetical, it was less hypothetical than competing theories. Faraday felt, as mentioned above "The safest course appears to be to assume as little as possible" and immaterial atoms came closest to reflecting reality:

"... all our perception and knowledge of the atom, and even our fancy, is limited to ideas of its powers: what thought remains on which to hang the imagination of (a nucleus) independent of the acknowledged forces? A mind just entering on the subject may consider it difficult to think of the powers of matter independent of a separate something to be called *the matter*, but it is certainly far more difficult, and indeed impossible, to think of or imagine that *matter*, independent of the powers. Now the powers we know and recognize in every phenomenon of the creation, the abstract matter in none; why then assume the existence of that of which we are ignorant, which we cannot conceive, and for which there is no philosophical necessity?"

The theory recommended itself also by the fact that it not only accounted for phenomena in a more complete manner than any other general hypothesis, but that it also provided a basic point of view from which to see physical reality. Davy was one of the first in the nineteenth century to realize the importance of structure in explaining sensible qualities. As we shall see, when Faraday discovered some new effect, his immediate thought was that it involved either a peculiar form or change in form of the arrangement of the constituent particles.

Finally there was the ability of the theory to predict new effects and, as it actually led to new discoveries this reinforced its claims to truth in Faraday's mind. The hold this hypothesis had on Faraday cannot be over-emphasized. He thought, almost instinctively, in terms of immaterial atoms and there are many passages in his works which make little or no sense unless one is aware of Faraday's theoretical frame of reference.

4. ELECTROLYSIS, STATIC INDUCTION AND CONDUCTION

In order to illustrate how Faraday used the Boscovichean concept, let us now examine one phase of the mighty achievement set down in the *Experimental Researches in Electricity*. Since Faraday carefully built his theory, each new fact being added in its proper place to the edifice of theory, it would be well to select the illustrative example from the earlier researches. Let us, therefore, consider the series of researches in the 1830's in which Faraday revealed the basic unity of electrolytic conduction, electrostatic induction and ordinary electrical conduction, and in which, by challenging the orthodox view of action at a distance, he laid the foundations for the modern theory of the field.

In order properly to understand the daring and originality of Faraday, we must first briefly glance at the conventional ideas of these three aspects of electrical science. The almost universal explanation of all electrical effects before Faraday was to be found in the assumption of one or two imponderable electrical fluids whose attractions and repulsions, under specified conditions, accounted for all observable facts. Sometimes, when faced with specific events, these explanations became a bit clumsy. How, for example, account for the appearance of the products of electrolysis at the poles of a voltaic cell? If a water

molecule is split into hydrogen and oxygen, how does each gas get to its respective pole, and why do they not simply bubble up in the middle? Or how is it possible to pass acids through alkaline electrolytes without there being any chemical reaction, as Davy had done? Dozens of speculations were forthcoming—such as that which suggested that the electrical fluids carried the hydrogen and oxygen in opposite directions through the wires and deposited them at the poles—but none which could satisfactorily cover all the phenomena.

Electrostatic induction seemed simpler, as being merely the mutual attraction or repulsion (at a distance) of the electrical fluid(s) across a non-conducting medium. The fluid(s) could be 'thrown in' or 'out' of bodies at will and was therefore separable from ponderable matter. Ponderable matter itself could be divided into two classes—conductors and non-conductors. Two consequences of this view should be noted. If electricity is separable from ponderable matter, it ought to be possible to create an absolute charge; conductors and non-conductors must differ fundamentally on the atomic level, and the distinction with respect to electricity implies two basically different *kinds* of matter.

The electric current was nothing more than the free passage of the electric fluid(s) through conductors completely analogous to the flow of water through pipes. How such a current could give rise to magnetic effects and induce a current in another wire, however, was difficult to explain.

Faraday began his investigations on the nature of conduction as a result of his discovery of electromagnetic induction. Having found that a magnet could induce a momentary electric current in a neighbouring wire under certain conditions, the next step was to show that the magnetism of a current-carrying helix could do likewise. This in turn raised two questions: what was the electric current, and what was the state of the secondary when a steady current was passing in the primary? Faraday's attempts to answer the first question were to occupy him the rest of his life but it is interesting to see that he considered the possibility that the 'current' was a particular static arrangement of the particles—a polarization, and not a flow. This he reluctantly rejected since a magnetic needle placed under a wire connected to one end of a voltaic pile but not to the other shows no deviation; the moment contact with the other end is made, the needle moves indicating that something has passed. Faraday's working definition of a current, however, is worth citing for it is wider than that which immediately comes to mind.

"By current I mean anything progressive, whether it be a fluid or Electricity or vibrations or generally progressive forces."

If the current itself is not an arrangement, must it not be preceded by some kind of change in the relations of the ultimate particles? What, for example, is the condition of the secondary after the first surge of current has passed through it when the primary circuit is made? It has returned, seemingly, to its normal state; but this is only appearance for,

"... it resists the formation of an electrical current in it, whereas, if in its common condition, such a current would be produced, and when left uninfluenced it has the power of originating a current, a power which the wire does not possess under common circumstance."

Attempts were made to detect this state, which Faraday clearly felt ought to manifest itself as electrical or magnetic attractions or repulsions, but to no avail.

Nevertheless, he felt able to describe the condition of the molecules of the wire; it was, he said, a state of tension, in which the constituent particles were strained along the direction followed later by the current. This electro-tonic state, as it was named, was not restricted to the secondary in the electromagnetic arrangement. Faraday immediately seized upon it for the light it shed upon a totally different area—namely upon the problem of electrolysis and the separation of the elements under electric influence.

“ The reason given with regard to metals extends also to fluids and all other conductors, and leads to the conclusion that when electric currents are passed through them they also assume the electro-tonic state. Should that prove to be the case, its influence in voltaic decomposition, and the transference of the elements to the poles, can hardly be doubted. In the electro-tonic state the homogeneous particles of matter appear to have assumed a regular but forced electrical arrangement in the direction of the current, which if the matter be undecomposable, produces, when relieved, a return current: but in decomposable matter this forced state may be sufficient to make an elementary particle leave its companion, with which it is in a constrained condition, and associate with the neighbouring similar particle, in relation to which it is in a more natural condition, the forced electrical arrangement being itself discharged or relieved, at the same time, as effectually as if it had been freed from induction. But as the original voltaic current is continued, the electro-tonic state may be instantly renewed, producing the forced arrangement of the compound particles, to be as instantly discharged by a transference of the elementary particles of the opposite kind in opposite directions, but parallel to the current.”

Only a few months later, further experiment on electromagnetic induction caused Faraday to reject the electro-tonic state, *but only for the secondary*, not for electrochemical phenomena. In that area this concept provided certain experimentally testable ideas. If Faraday were right, then ‘ action at a distance ’ between the two poles could not also be right. This could be examined by eliminating poles. Thus if a static electricity machine were made to discharge through a piece of absorbent paper soaked in an electrolytic solution and into the air, electricity would pass without there being any centre of attraction towards which the elements of the electrolyte could be attracted. There was, nevertheless, electrolytic action, leading Faraday to conclude that

“ the effects of decomposition would seem rather to depend upon a relief of the chemical affinity in one direction and an exaltation of it in the other, rather than to direct attractions and repulsions from the poles, etc., etc.”

A further testable difference between Faraday’s view of the mechanism of electrolytic dissociation and decomposition and the commonly held view concerned the elements of the decomposing electrolyte. According to the ordinary view, the positive and negative electric forces literally tore the compound asunder, attracting the electro-positive and electro-negative elements to opposite poles. During their passage, the elements supposedly existed as free chemical agents, as shown by the intensification of the colour of an indicator as the particles converged on the pole. In Faraday’s theory, the elements were passed along ‘ hand to hand ’ as in an American square dance, so that at any point both the electro-positive and electro-negative elements were in combination but passing by one another in opposite directions. In order to decide between these explanations, the effect of diffusion of the indicator must be eliminated and the process slowed down as much as possible. The arrangement adopted by Faraday was extremely ingenious and characteristic of his ability to devise experiments capable of producing exactly those effects to be studied while excluding possible sources of error.

Faraday made a number of jellies capable of conducting a current and containing various electrolytes. He then arranged things as shown in fig. 2. (1) is the positive pole ; (2) litmus paper just wetted (without running) with distilled water; (3) unsaline jelly; (4) litmus paper wetted as above; (5) jelly containing sodium sulphate; (6) turmeric paper wetted as above; (7) unsaline jelly; (8) turmeric paper wetted as above; (9) negative pole. When contact was made, both the litmus paper at (2) and the turmeric paper at (8) turned colour, indicating the presence of acid and alkali at the poles. At (4) and (6) nothing happened and Faraday concluded:

"Hence the transference was good, ready and effective, but the evolution seemed to be altogether at the poles. No signs of the free acid or alkali in its transit appeared."

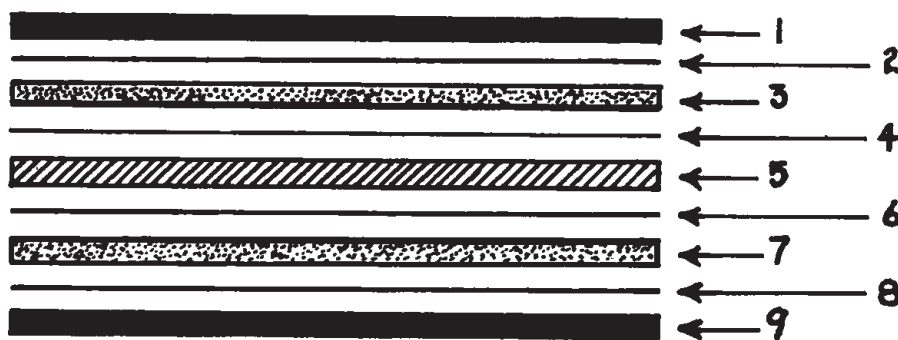


Fig. 2. Faraday's experiment on ionic migration.

Having proved, at least to his own satisfaction, that the state of tension existed during electrolysis, he now turned his attention to the whole *process* of electrolytic decomposition. The next problem was to determine what caused the state of tension, whose release and immediate re-creation constituted, in time, the electric current. We must not forget that Faraday was basically a chemist and that he saw these problems as chemical ones. As he wrote time and time again, "the forces termed chemical affinity and electricity are one and the same".

By 1834, the theory of immaterial atoms, capable of deformation and strain by the mutual action of their surrounding forces enabled him to give a complete description of electrolysis, based on experimental facts.

"Assuming it sufficiently proved, by the preceding experiments and considerations, that the electro-motive action depends, when zinc, platina, and dilute sulphuric acid are used, upon the mutual affinity of the metal zinc and the oxygen of the water . . . it would appear that the metal, when alone, has not power enough under the circumstances, to take the oxygen and expel the hydrogen from the water, for, in fact no such action takes place. But it would also appear that it has power so far to act, by its attraction for the oxygen of the particles in contact with it, as to place the similar forces already active between these and the other particles of oxygen and the particles of hydrogen in the water, in a peculiar state of tension or polarity, and probably also at the same time to throw those of its own particles

which are in contact with the water into a similar but opposed state. Whilst this state is retained, no further change occurs; but when it is relieved, by completion of the circuit, in which case the forces determined in opposite directions, with respect to the zinc and the electrolyte, are found exactly competent to neutralize each other, then a series of decompositions and recompositions takes place amongst the particles of oxygen and hydrogen constituting the water, between the place of contact with the platina and the place where the zinc is active; these intervening particles being evidently in close dependence upon and relation to each other. The zinc forms a direct compound with those particles of oxygen which were, previously, in divided relation to both it and the hydrogen: the oxide is removed by the acid, and a fresh surface of zinc is presented to the water, to renew and repeat the action."

In this explanation, note that there is one weak place in the argument; this is the existence of the electro-tonic state. It can only be inferred from the spark that will pass when the wires connecting the opposite poles of a voltaic battery are brought close together. Faraday argued that as the spark occurs before metallic contact is made and therefore before the electrolytic action could begin, there must be a pre-existent state of tension. But he would like to detect it, as it existed, not infer its presence from its effects. In May, 1833, he devised an experiment for this purpose. In view of the discovery of the rotation of polarized light in a magnetic field in 1845, the following test for internal strain, as in the electro-tonic state, deserves special attention.

"Thinking it possible that the discharge of the electric forces by the successive decompositions and recompositions of the particles of the electrolyte might neutralize and therefore destroy any effect which the first state of tension could by possibility produce, I took a substance which, being an excellent electrolyte when fluid, was a perfect insulator when solid, namely, borate of lead, in the form of a glass plate, and connecting the sides and the edges of this mass with the metallic plates, sometimes in contact with the poles of a voltaic battery, and sometimes even with the electric machine, for the advantage of the much higher intensity then obtained, I passed a polarized ray across it in various directions, as before, but could not obtain the slightest appearance of action upon the light. Hence I conclude, that notwithstanding the new and extraordinary state which must be assumed by an electrolyte, either during decomposition (when a most enormous quantity of electricity must be traversing it), or in the state of tension which is assumed as preceding decomposition, and which might be supposed to be retained in the solid form of the electrolyte, still it has no power of affecting a polarized ray of light; for no kind of structure or tension can in this way be rendered evident."

The 1845 discovery lies beyond the scope of this article, but we cannot pass on without noting what a remarkable conclusion Faraday, the so-called strict empiricist, reached. The test showed, said Faraday, not that the electro-tonic state did not exist, but that the state of tension (for which there was no direct evidence) had no power of affecting a polarized ray of light! Even so was Faraday caught in his own hypothesis despite his extraordinary sensitivity to the pitfalls of theory.

If the electro-tonic state exists in a substance which is an electrolyte when fluid and an insulator when solid, then what is it that constitutes the difference between the two states? Why, in short, should the substance conduct when fluid and not conduct when solid? There is one obvious difference between the two; in the fluid state the particles are mobile while in the solid state they are not. Conduction, therefore, in this view, is the breakdown of the electro-tonic state under the tension created by the impressed electric force. But is this not precisely what happens when the tension across a so-called non-conductor becomes so great that discharge takes place? In short, are not

conduction and non-conduction merely a matter of degree and not a fundamental distinction between different substances? The evolution of these ideas is again best told in Faraday's words:

"As, therefore, in the electrolytic action, induction appeared to be the first step, and decomposition the second (the power of separating these steps from each other by giving the solid or fluid condition to the electrolyte being in our hands); as the induction was the same in its nature as that through air, glass, wax, etc., produced by any of the ordinary means; and as the whole effect in the electrolyte appeared to be an action of the particles thrown into a peculiar or polarized state, I was led to suspect that common induction itself was in all cases an action of contiguous particles, and that electrical action at a distance (i.e. ordinary inductive action) never occurred except through the influence of the intervening matter."

Once again, there was a clear-cut and testable difference between Faraday's and the commonly-held theory: induction, as action at a distance, should take place along straight lines; induction, as the result of the action of contiguous particles under tension, should take place in curves. The model was drawn once more from electrochemistry, since the deposition of elements uniformly on the electrodes clearly proved action in curves, not in straight lines. Mapping the 'lines of force' in an enormous number of experiments Faraday was able to show that induction *did* take place in curves. This, to him, was conclusive.

It also led him to one final result, the discovery of specific inductive capacity for,

"if induction be an action of contiguous particles, and also the first step in the process of electrolyzation . . . there seemed reason to expect some particular relation of it to the different kinds of matter through which it would be exerted, or something equivalent to a specific electric induction for different bodies, which, if it existed, would unequivocally prove the dependence of induction on the particles."

The seeming differences in the electrical properties of bodies could now be explained in terms of the capacity for deformation of the contiguous particles out of which these bodies were composed. The metals could sustain only a very low level of tension, so that a very small deforming force caused the rise and almost immediate collapse of the electro-tonic state. The metals, in short, were good conductors. In electrolytes, the strain led to the decomposition of the compound, relief of the strain coinciding with the liberation of a particle of the elements at both poles. In insulators, the particles were able to withstand much greater tensions but here, too, discharge could be effected by placing such strain on the linked particles that the chain broke and the polarized state collapsed.

We have now reached the end of our examination of this phase of Faraday's work. By 1837, he had brought all electrical phenomena under the universal law of induction. Is it not paradoxical that Faraday, cited constantly as the foe of theorizing in general and of atomism in particular, should have built so great an edifice upon the theory of immaterial atoms?

REFERENCES

- FARADAY, M., 1816-19, *A Course of Lectures on Chemistry delivered before the City Philosophical Society* (Manuscript: Institution of Electrical Engineers Library); 1844, 1855, *Experimental Researches in Electricity*, 3 vols. (London: Taylor & Francis); 1859, *Experimental Researches in Chemistry and Physics* (London: Taylor & Francis).
LAVOISIER, A., 1864-69, *Oeuvres Complètes*, 6 vols. (Paris: Imprimerie Impériale).
MARTIN, T., ed., 1932-36, *Faraday's Diary*, 8 vols. (London: G. Bell & Sons).